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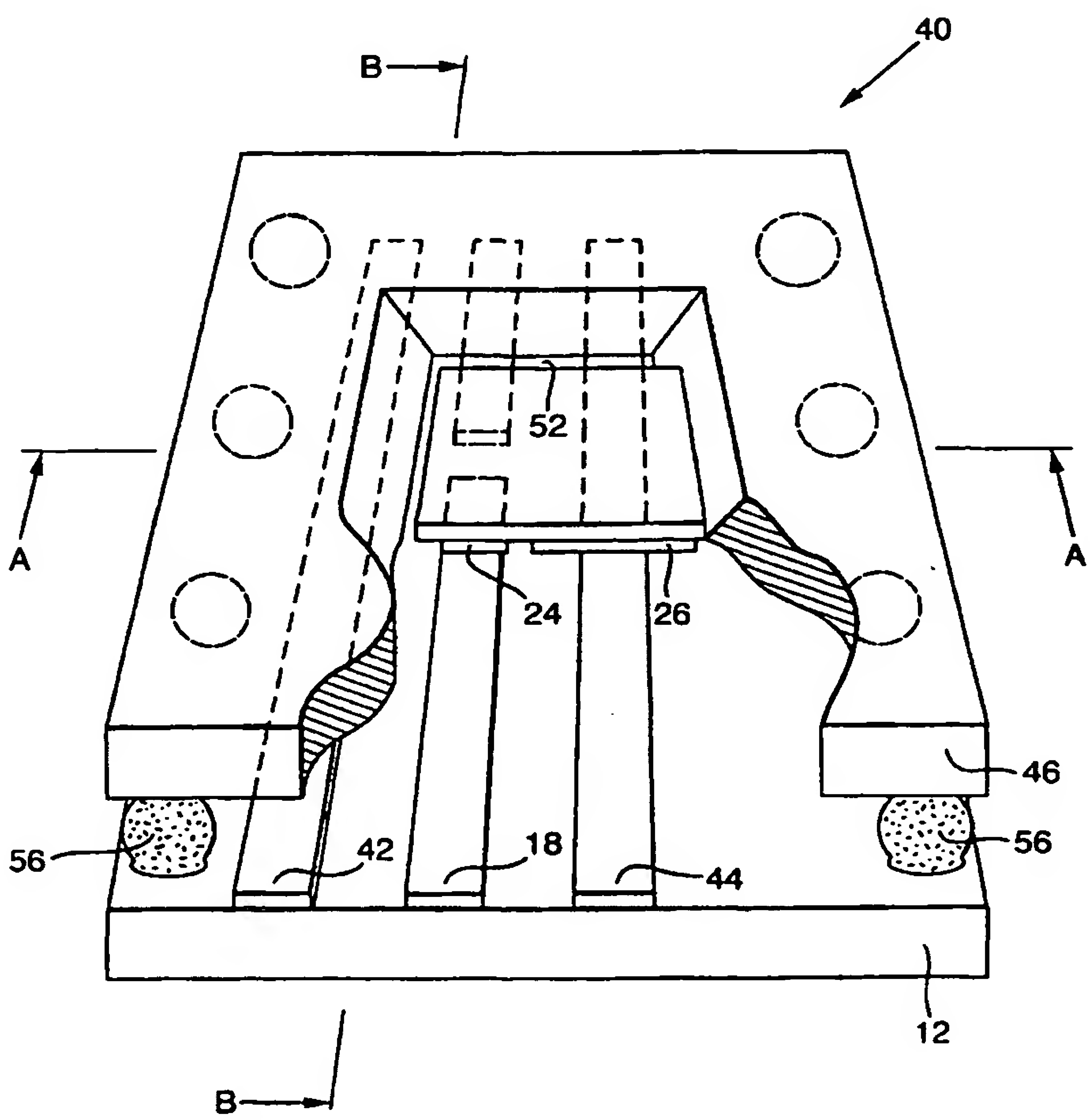
(54) Title: ELECTRICAL SWITCHES



(57) Abstract: An electrical switch (40) comprises: electrical contacts (18, 20, 24) and an actuator (26) for moving the contacts relative to each other between an open state and a closed state. The actuator (26) includes a deformable member (14), preferably a cantilever, which includes a piezoelectric material (26) which is operable to undergo a dimensional change in response to an electric field applied thereacross for moving the contacts (24) relative to each other. The deformable member (14) is microfabricated from a first substrate (46) which is joined to a second substrate (12) including at least some of the contacts (18, 20) to form an assembly.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

ELECTRICAL SWITCHES

This invention relates to electrical switches and is more especially, although not exclusively, concerned with switches for switching microwave signals in for example phased array antenna systems as used in communications and radar applications.

Switching of microwave signals is necessary in many applications such as cellular communication systems, satellite direct broadcast, terrestrial broadcast and systems which utilise phased array antenna systems. For example, in the amplification stages of a phased array system for radar or communication, microwave power is switched through a power amplifier during transmission and through a low noise amplifier during reception.

Another example of switching of microwave signals is in steering a beam produced by a phased array antenna using time delay phase shifting in which microwave signals are switched along transmission lines of different lengths. Each transmission line leading up to an antenna element of the array is divided into a number of sections, each section having a relatively short transmission length and a relatively long transmission length. A switch is provided for each section such that a microwave signal can be switched to be transmitted through either the short length or the long length. By selectively operating the switches along the transmission line, its transmission length can be varied thus varying its transmission time and thereby introducing a phase delay to the microwave signal. A beam produced by the array can be steered by controlling the phase delays in a number of such lines.

It is known to switch microwave signals using solid state switches based on MESFETs (Metal Semiconductor Field Effect Transistor) or PIN diodes which can be connected in series or in shunt with the transmission line. Although solid state switches can provide rapid switching times of the order of a few nanoseconds problems exist with such switches. Typically they cause a loss of 0.5 to 2 dB for signals in the X-Band (8-12GHz), and due to their non-linear characteristics they exhibit power compression characteristics at relatively low power levels (of the order 27-30 dBm for MESFETs). As a consequence the use of solid state switches is limited to applications where significant losses can be tolerated and to low power applications. Furthermore switches based on diodes consume a relatively high amount of d.c. power, typically of the order of 20mA per diode which can amount to an appreciable power consumption in applications such as phased array antennas where several thousand such switches may be required.

It is also known to switch microwave signals using electrostatically actuated mechanical switches. One such switch comprises a polysilicon cantilever beam which is supported above a substrate such that a conductor at the free end of the beam overlays a gap in a transmission line provided on the substrate. The substrate and cantilever are provided with complementary electrodes which are used to actuate the switch. When an actuating voltage is applied across the electrodes the electrostatic force of attraction between the electrodes causes the cantilever to bend such that the conductor bridges the gap in the transmission line thereby closing the switch. Electrostatic switches have also been proposed which comprise a membrane which is supported by a peripheral frame. The switch is activated by the electrostatic force of attraction between the membrane, which may be metallic, and a corresponding electrode on the substrate. Although electrostatic

switches, due to the physical separation of the contacts, provide a higher electrical isolation (up to 120dB) compared with that of solid state switches, they require a high operating voltage, typically of the order of 20 to 100V, making them TTL (Transistor Transistor Logic) and CMOS (Complementary Metal Oxide Semiconductor) incompatible.

The present invention has arisen in an endeavour to provide an electrical switch which is capable of switching microwave signals and which at least in part overcomes the limitations of the known switches.

According to the present invention an electrical switch comprises: electrical contacts and an actuator for moving the contacts relative to each other between an open state and a closed state, and is characterised in that the actuator includes a deformable member comprising a piezoelectric material operable to undergo a dimensional change in response to an electric field applied thereacross for moving the contacts relative to each other and the deformable member is microfabricated from a first substrate which is joined to a second substrate including at least some of the contacts to form an assembly. A particular advantage of a switch in accordance with the invention is that it only requires low voltages, of the order of a few volts, to actuate the switch making it compatible with TTL and CMOS logic. Being a simple mechanical device it provides a high isolation (typically 25dB at 50GHz) in the open state and a low-loss contact typically in the order of about 0.1dB when switching signal over a frequency range of d.c. to 50 GHZ. Furthermore a switch according to the invention is relatively simple in construction and so can be microfabricated in miniature form having a typical dimension of 2mm x 2mm.

It is also robust and reliable.

Preferably the piezoelectric material comprises lead zirconate titanate (PZT). A particular advantage in using a piezoelectric material is that its dimensional change is substantially linear with applied electric field. Preferably the actuator comprises a film of said material and two or more electrodes for applying an electric field thereacross. The piezoelectric film or similar is preferably deposited using a sol-gel technique. Preferably the piezoelectric material is in layered form to maximise deflection while minimising the electric field. The field applied to each layer is preferably applied in opposite directions to maximise deflection.

In one arrangement the deformable member is planar in form such as a cantilever. Alternatively the deformable member comprises a strip supported at opposite edges or a membrane supported around its periphery.

In a preferred embodiment the contacts on the first or second substrate are configured such as to provide an electrical path having a break therein and the corresponding contact on the second substrate or first substrate is configured to electrically bridge said break when the switch is in a closed state. Alternatively the switch further comprises a dielectric layer on at least one of said electrical contacts such that an electrical signal is capacitively coupled between said contacts when the switch is in a closed state.

Advantageously the first substrate and its associated deformable member and the second substrates comprise different materials such as bulk single-crystal silicon and gallium

arsenide respectively when it is intended to use the switch to switch microwave frequency signals.

In a particularly preferred arrangement the second substrate is planer in form and preferably comprises an integrated circuit to which the first substrate is bonded by, for example, flip chip solder bonding. Thus according to a further aspect of the invention an integrated circuit incorporates one or more switches as described above.

A switch in accordance with the invention find particular applications in a phased array antenna system for transmitting and/or receiving beams of microwave radiation. For example they can be used to switch different transmission lengths to provide variable phase delays. Alternatively they can be used to switch an antenna between transmission and reception modes or to switch between a transmission antenna or a reception antenna.

Phased array antennas are known in which a common antenna is connected to a circulator which, in turn, is connected to both the power amplifier and the low noise amplifier. Replacing the circulator with a plurality of switches according to the invention provides improved isolation of the low noise amplifier and, due to reduced insertion loss, less waste of transmitted power and a reduced overall noise figure.

According to yet a further aspect of the invention a phased array antenna incorporates one or more electrical switches as described above.

In order that the invention may be better understood three electrical switches in accordance with the invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a schematic isometric representation of a cantilever switch;

Figure 2 is a side view of the cantilever switch of Figure 1;

Figure 3 is an end view of the cantilever switch of Figure 1;

Figure 4 is an isometric partial cut away of second cantilever switch in accordance with the invention;

Figure 5 is a cross section along the line AA of the switch of Figure 4;

Figure 6 is a cross section along the line BB of the switch of Figure 4;

Figure 7 is a schematic representation of a membrane switch in accordance with the invention in an "open" state;

Figure 8 shows the membrane switch of Figure 7 in a "closed" state; and

Figure 9 is a schematic representation of a switching arrangement for use in a phased array antenna system.

A switch in accordance with a first embodiment of the invention is shown in Figures 1, 2 and 3 which show a single pole single throw (SPST) cantilever switch 10 which comprises an electrically insulating base or substrate 12 upon which a cantilever 14 is mounted in fixed relation and is separated from the substrate 12 by a gap 16. The substrate 12 comprises a material which is insulating at the frequency of the signals the switch is intended to switch. Thus when the switch is intended for switching microwave signals, such as for example for frequencies up to 50 GHZ, the substrate comprises a material having a low loss at these frequencies such as for example gallium arsenide (GaAs), gallium nitride (GaN), aluminium nitride (AlN), sapphire, quartz, silicon:germanium or a ceramic material such as alumina or a low temperature co-fired ceramic (LTCC). For operations with lower frequency signals the substrate preferably comprises silicon (Si). The cantilever 14 can comprise the same material as the substrate 12 though for ease of manufacture it is preferably made of silicon, most preferably bulk single-crystal silicon.

Upon the surface of the base 12 opposite the cantilever 14 there are provided electrically conducting tracks 18, 20 which are configured to form an electrically insulating gap 22 which is located under the cantilever 14. A complementary and opposing electrically conducting contact 24 is provided on the cantilever 14 such as to overlay the gap 22. The contact 24 is dimensioned such that when the switch is actuated, as described below, it bridges the gap 22 between the conducting tracks 18, 20 and electrically connects the tracks 18, 20.

An actuator, generally denoted 26, is provided on an upper surface of the cantilever 14. The actuator 26 comprises a film or thin layer of piezoelectric material 28, most preferably lead zirconate titanate (PZT), which is sandwiched between metallic electrode layers 30, 32. The actuator 26, more specifically the piezoelectric material layer 28, is coupled to the cantilever 14 such that deformation of the layer 28 will cause a corresponding deformation of the cantilever 14.

In operation of the switch 10 when a potential difference is applied between the electrodes 30, 32 the resultant electric field across the piezoelectric film 28 causes its length to increase relative to the length of the cantilever 14 and this causes the cantilever 14 to bend in a direction towards the base 12. The bending of the cantilever 14 brings the contacts 24 into electrical contact with the conducting tracks 18, 20, electrically bridging the gap 22 thereby "closing" the switch. Removal of the electric field allows the cantilever 14 to straighten and thus "opens" the switch. To cause the switch to "open" more rapidly the direction of the electric field can be reversed rather than being removed thereby causing the length of the piezoelectric layer to contract. It will be appreciated that in alternative arrangements the actuator can be located elsewhere on the switch such as for example on the underside of the cantilever in which case it is operable to "close" the switch through a contraction in the length of piezoelectric layer. Furthermore it will be appreciated by those skilled in the art that alternative switch configurations can be readily devised which "open" on application of electric field and "close" on its removal or reversal.

A cantilever switch in accordance with a second embodiment of the invention is shown

in Figures 4, 5 and 6 which show a SPDT cantilever switch 40 for switching the signals from d.c to 50GHz. For consistency the same reference numerals are used to denote like parts to those of the switch of Figure 1 to 3.

The switch 40 and its method of construction is now described by way of reference to Figures 4, 5 and 6. The switch 40 is of hybrid construction in which the base 12 is of suitable low loss microwave substrate, most preferably GaAs, and the cantilever is made of bulk single-crystal silicon. On the GaAs substrate 12 the conducting tracks 18, 20, which preferably comprise gold, are deposited using a suitable method such as metal deposition evaporation, sputtering or plating up. The conducting tracks 18, 20 are flanked by coplanar parallel conducting tracks 42, 44 deposited in a like manner. The tracks 42, 44, which are unbroken, provide ground lines whilst the tracks 18, 20 provide the switchable signal line. Typically each of the tracks 18, 20, 42, 44 is approximately 50μm wide and spaced apart by approximately 60μm. The gap 22 between the tracks 18, 20 is of the order of 200μm which, in conjunction with a 5-11μm gap between the cantilever and the substrate 12, provides an electrical isolation in the "open" state of approximately 30dB.

The cantilever 14, which is of silicon, is fabricated separately to that of the GaAs substrate. The cantilever 14 is micromachined into a silicon substrate 46 by firstly etching downwards from the surface to create a rectangular pit 48 having sloping sides and a thin bottom 50 of the order of 20μm thickness. A gap 52 is then etched around three of the edges of the bottom 50 to provide the cantilever 14 having a free end 54. In the context of this patent application micromachining is to be interpreted as meaning

those processes which are used to create three dimensional structures at a μm scale such as for example those used in the fabrication of silicon based integrated circuits and include for example bulk chemical etching, vapour deposition, reactive ion beam sputter deposition/etching or milling, laser machining and ion implantation.

The contact 24 and electrode 30 are deposited on the planar surface of the cantilever 14 and a film 28 (typically this is of order 1μm thickness) of PZT deposited over the electrode 30. Most conveniently the PZT film is deposited by sol-gel (solvent-gel) deposition by spinning a layer of sol-gel over the planar surface of the substrate 46, sintering the substrate and then etching away unwanted areas of PZT. Although the actuator 26 can be provided on the upper surface of the cantilever it is preferred to provide it on the lower planar surface due to its ease of fabrication. Finally the second electrode 32 of the actuator 26 is deposited.

The switch 40 is finally assembled by joining the substrates 12 and 46 using flip chip solder bonding. This process provides good placement accuracy and height control by using solder bumps 56 which are located on respective metallic pads which are deposited when the tracks 18, 20, 42, 44 and electrode 32 are deposited.

The operation of the switch is identical to that described above such that electrical actuation of the PZT film 28 causes the cantilever 14 to bend thus bringing the metal contact 24 into contact with the signal tracks 18, 20 thereby bridging the gap 22 and closing the switch 40. In the foregoing description the switch 40 is depicted as a discrete device, it will be appreciated however that a particular advantage of this switch 40 is that

it can be readily fabricated as part of an integrated circuit in which the substrate 12 is the integrated circuit. In such an arrangement the conducting tracks 18, 20, 42, 44 and their interconnection to the circuit are deposited on the surface of the integrated circuit and the cantilever layer, which is fabricated separately, is then flip chip bonded onto the surface of the circuit. The electrical connection between the electrode layers 30, 32 of the piezoelectric actuator 26 and the circuit is conveniently achieved via the solder bumps 56 used in the flip chip bonding.

A particular advantage of a switch having a hybrid construction is that the optimum materials and fabrication techniques can be utilised for the cantilever and substrate. For example silicon is an ideal material for the cantilever due to its thermal stability and due to it being inexpensive and readily machinable using micromachining techniques. Although at microwave frequencies silicon is too lossy its effect is minimised by the small area of the contact 24 over which such a signal passes. In contrast GaAs provides an ideal low loss substrate though it tends to be relatively more brittle and difficult to machine. Furthermore the deposition of temperature of a piezoelectric thin film, such as PZT, is often greater than the decomposition temperature of GaAs.

A third embodiment of the invention is shown in Figures 7 and 8 which respectively show a membrane switch 60 in an "open" and "closed" configuration. The switch 60 comprises a base or substrate 62, typically of GaAs for microwave operation, carrying a rectangular frame 64 which circumferentially supports a membrane or diaphragm 66 fabricated of silicon, silicon nitride or silicon oxide. For ease of fabrication the diaphragm 66 is not supported continuously around its periphery and in one embodiment

the membrane is secured to the substrate using flip chip solder bonding such that the solder bumps comprise the frame. In another embodiment the membrane comprises a strip supported at opposite ends.

The membrane 66 carries on an upper surface 68 a PZT thin film actuator 70 and on a lower surface 72 a first metal signal carrying line 74. The lower surface 72 and the signal carrying line 74 face the base 62. A second metal signal carrying line 76 is provided on an upper surface 78 of the base. Electrical actuation of the PZT actuator 70 causes the membrane 66 to deform so that it adopts a bowed configuration (as represented in Figure 8) thereby bringing the signal carrying lines 74 and 76 closer together. In this "closed" configuration they are electrically coupled together by capacitive coupling through a dielectric layer 80 present on the second signal carrying line 76. In an alternative arrangement both the signal carrying lines are provided on the substrate and the gap between them is bridged by a corresponding contact on the underside of the membrane. This latter contact arrangement is preferred for switches intended to operate at microwave frequencies since it reduces the switches loss by minimising the surface area of silicon over which the signal passes.

The switches described in the foregoing can be provided as small discrete packaged devices (typically a few millimetres square) or mounted onto microwave circuits prior to packaging. Such micro-switches can be used as broad band switches, for example in the range d.c to 50GHz. Their simple mechanical action provides low loss (typically less than 0.1dB) and high isolation (for example 50dB at 2GHz and 27dB at 50GHz). A separation between the contacts of 2μm in the "open" state is sufficient to achieve

isolation of 25dB. Although switches according to the invention have a relatively low switching speed (10μs) compared to conventional PIN diode and MESFET switches which can operate as quickly as nanoseconds their speeds are still suitable for a wide range of applications. Piezoelectric actuation requires relatively low drive voltages, typically in the region of 3 to 5V. Such voltages are much lower than those required for electrostatic actuation.

The switches are suitable for use in phased array systems. They can be used to replace a circulator and provide low loss switching of an antenna connection between a power amplifier in transmission and a low noise amplifier in reception. Such an arrangement is shown in Figure 9. This shows an antenna arrangement used in a phased array system. A common transmit/receive line 90 is connected to two SPST switches 92, 94. The output 96 of the switch 92 is connected to an input of a power amplifier 98 and the output 100 of the second switch 96 is connected to the output of a low noise amplifier 102. Connected to the output of the power amplifier 98 and to the input of the low noise amplifier 102 are respective SPST switches 104, 106 . The second connection of each switch 104, 106 is connected to an antenna 108.

Each SPST switch comprises a switch according to the invention as described above. To transmit a microwave signal from the line 92 to the antenna 108, switches 92 and 104 are closed and switches 92, 94 are opened (as shown in Figure 9) thus connecting the common line 92 to the antenna 106 via the power amplifier 98 whilst isolating the low noise amplifier 102. The states of the switches are reversed to receive a microwave signal from the antenna 108 through the low noise amplifier 102.

Alternatively switches according to the invention can be used to switch between short and long transmission lengths to provide a transmission line having a variable length and thus phase delay. An arrangement of about 1000 antenna elements each fed by a track having about five or six sections having different transmission lengths can be used in a phased array system for satellite tracking, for example tracking satellites in a low earth orbit (LEO). Satellite communications typically occur in the region of 18 GHZ to 40GHz.

It will be appreciated by those skilled in the art that modifications can be made to the switches described which are within the scope of the invention. For example whilst in the embodiments described the switch is actuated using a piezoelectric material other electro-strictive materials can be used, such as for example PMN:PT (Lead Magnesium Niobate: Lead Titonate). In the context of this patent application an electro-strictive material is a material which undergoes a dimensional change in response to an applied electric field. An advantage of a piezoelectric material is that its change in dimension is substantially linear with applied electric field. It will be further appreciated that multiple layers of electro-strictive material to which opposing polarity electric fields are applied can be used to provide a larger deformation for a given actuating voltage.

Furthermore whilst SPDT switches have been described other forms of switches are envisaged such as single or multiple double throw switches.

Whilst the switch of the present invention is primarily intended for switching electrical

signals it is also envisaged that the switch can be used to switch other media such as for example optical signals. For example in one embodiment the electrically conducting tracks 18, 20 comprise optical waveguides which are fabricated within the substrate 62 and the contact 24 on the cantilever 14 is operable to act as a shutter which is movable into and out of the gap 22, thereby blocking or allowing the passage of light between the waveguides.

CLAIMS

1. An electrical switch (10; 40; 60) comprising: electrical contacts (18, 20, 24; 74, 76) and an actuator (26, 70) for moving the contacts relative to each other between an open state and a closed state, characterised in that the actuator (26, 70) includes a deformable member (14; 66) comprising a piezoelectric material (28, 70) operable to undergo a dimensional change in response to an electric field applied thereacross for moving the contacts relative to each other and the deformable member (14; 66) is microfabricated from a first substrate (46) which is joined to a second substrate (12; 62) including at least some of the contacts (18, 20; 76) to form an assembly.

2. A switch according to Claim 1 in which the piezoelectric material (28, 70) comprises lead zirconate titanate.

3. A switch according to Claim 1 or Claim 2 in which the piezoelectric material is a sol-gel deposited material.

4. A switch according to any preceding claim in which the deformable member is a membrane (66) or a cantilever (14).

5. A switch according to any one of claims 1 to 3 in which the deformable member comprises a strip supported at opposite edges.

6. A switch according to any preceding claim in which the first substrate (46) and its associated deformable member (14) comprise bulk single-crystal silicon.

7. A switch according to any preceding claim in which the second substrate (12, 62) comprises gallium arsenide, gallium nitride, aluminium nitride, sapphire, quartz, silicon: germanium, aluminium or a low temperature co-fired ceramic material.

8. A switch according to any preceding claim in which the contacts (18, 20) on the first (46) or second substrate (12) are configured such as to provide an electrical path having a break therein and wherein the corresponding contact (24) on the second substrate (12) or first substrate (46) is configured to electrically bridge said break when the switch is in a closed state.

9. A switch according to any preceding claim and further comprising a dielectric layer (80) on at least one of said electrical contacts (76) such that an electrical signal is capacitively coupled between said contacts (74, 76) when the switch is in a closed state.

10. An electrical switch according to any preceding claim in which the second substate (12, 62) is planar in form.

11. A switch according to any preceding claim in which the second substrate (12, 62) comprises an integrated circuit.

12. An integrated circuit incorporating one or more switches according to any preceding claim.

13. A phased array antenna incorporating one or more switches according to any preceding claim.

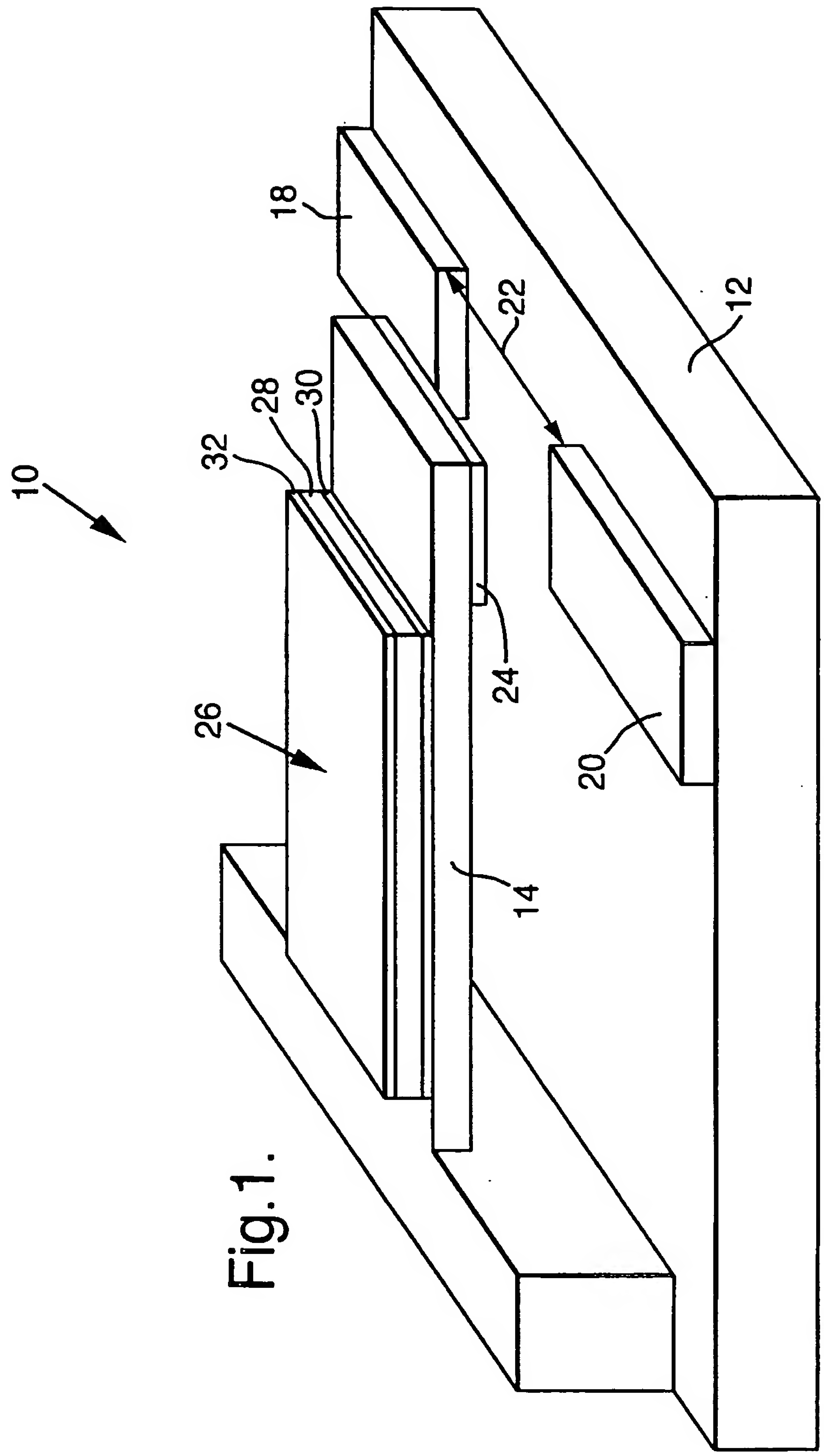

Fig.1.

Fig.2.

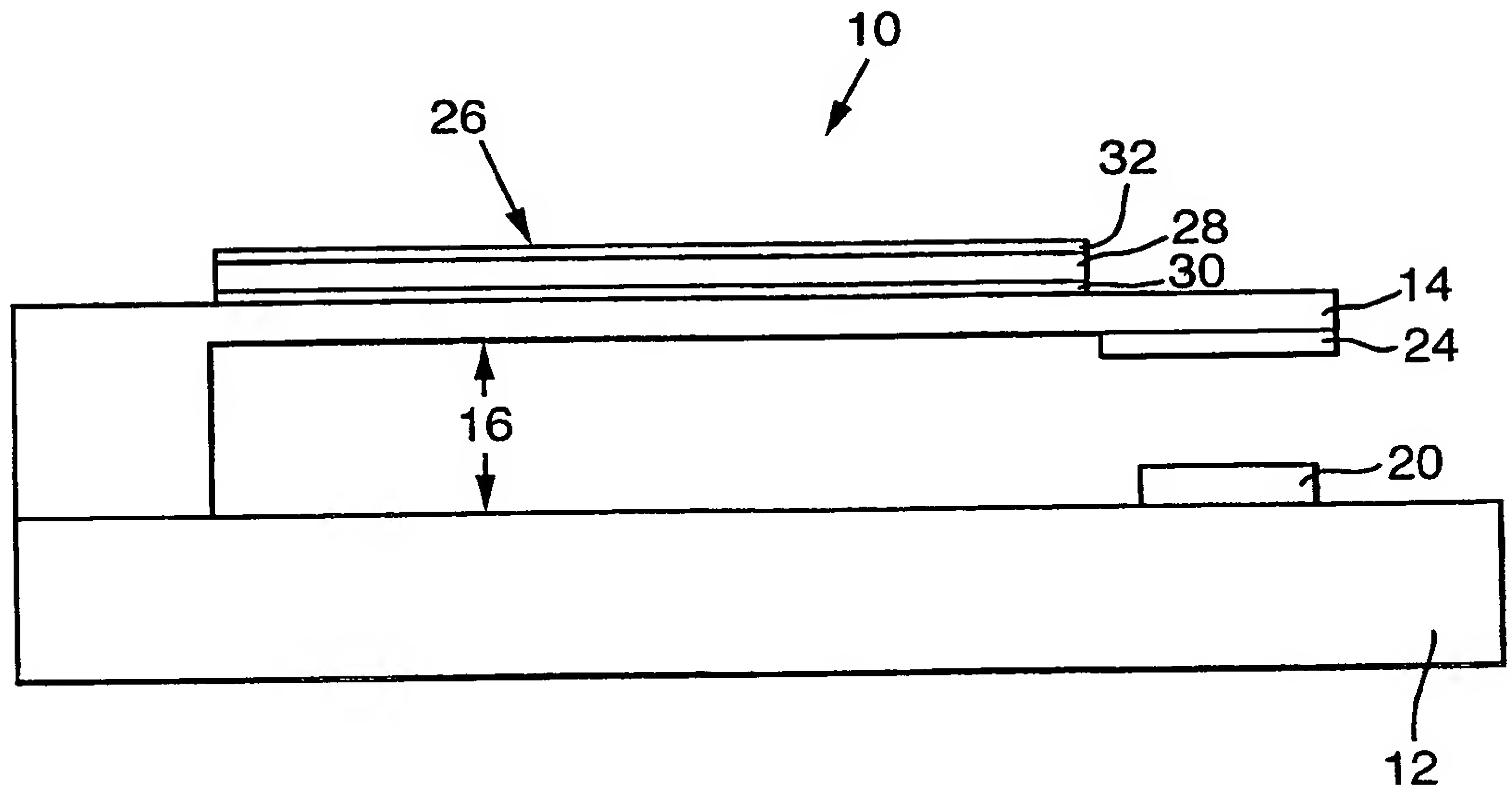

Fig.3.

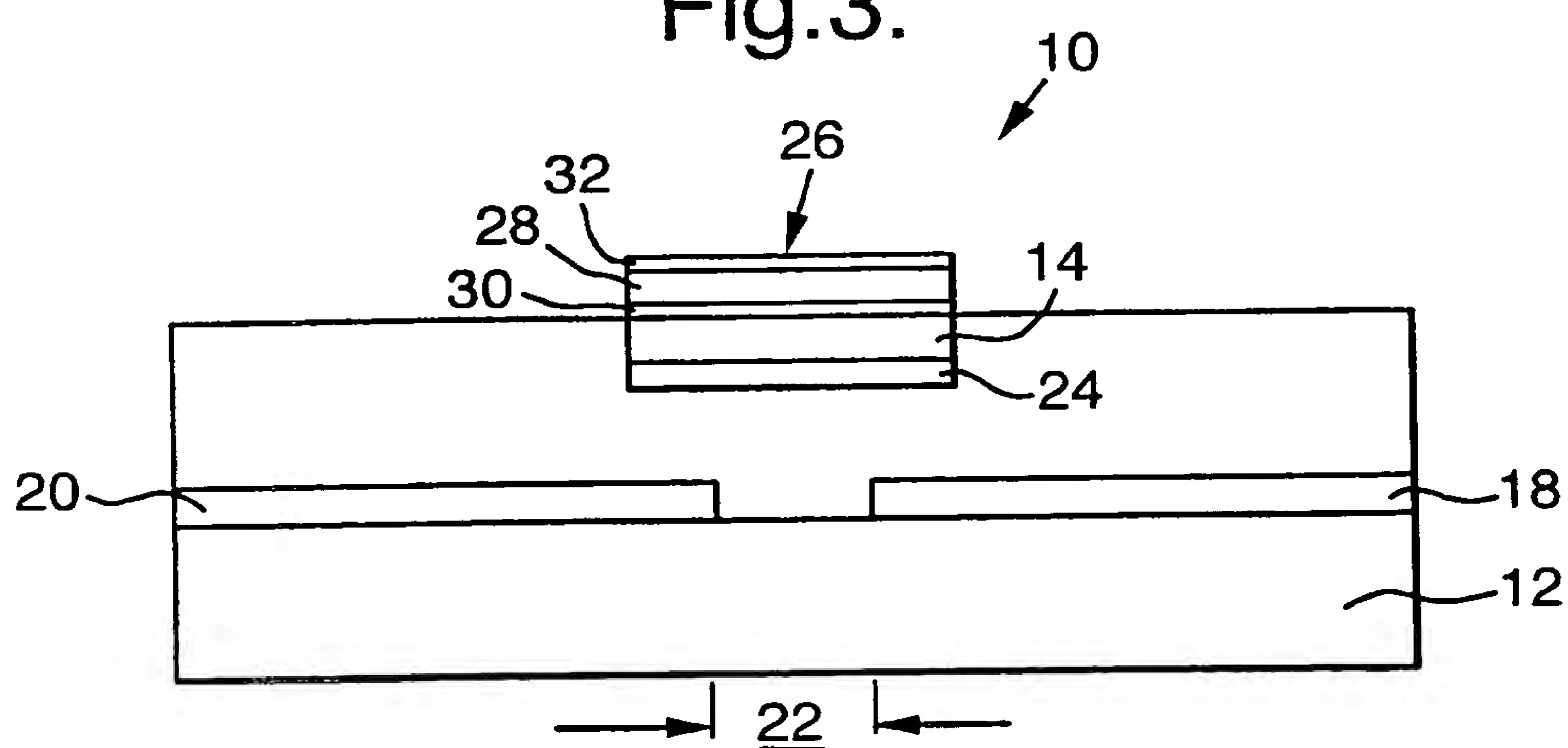

Fig.4.

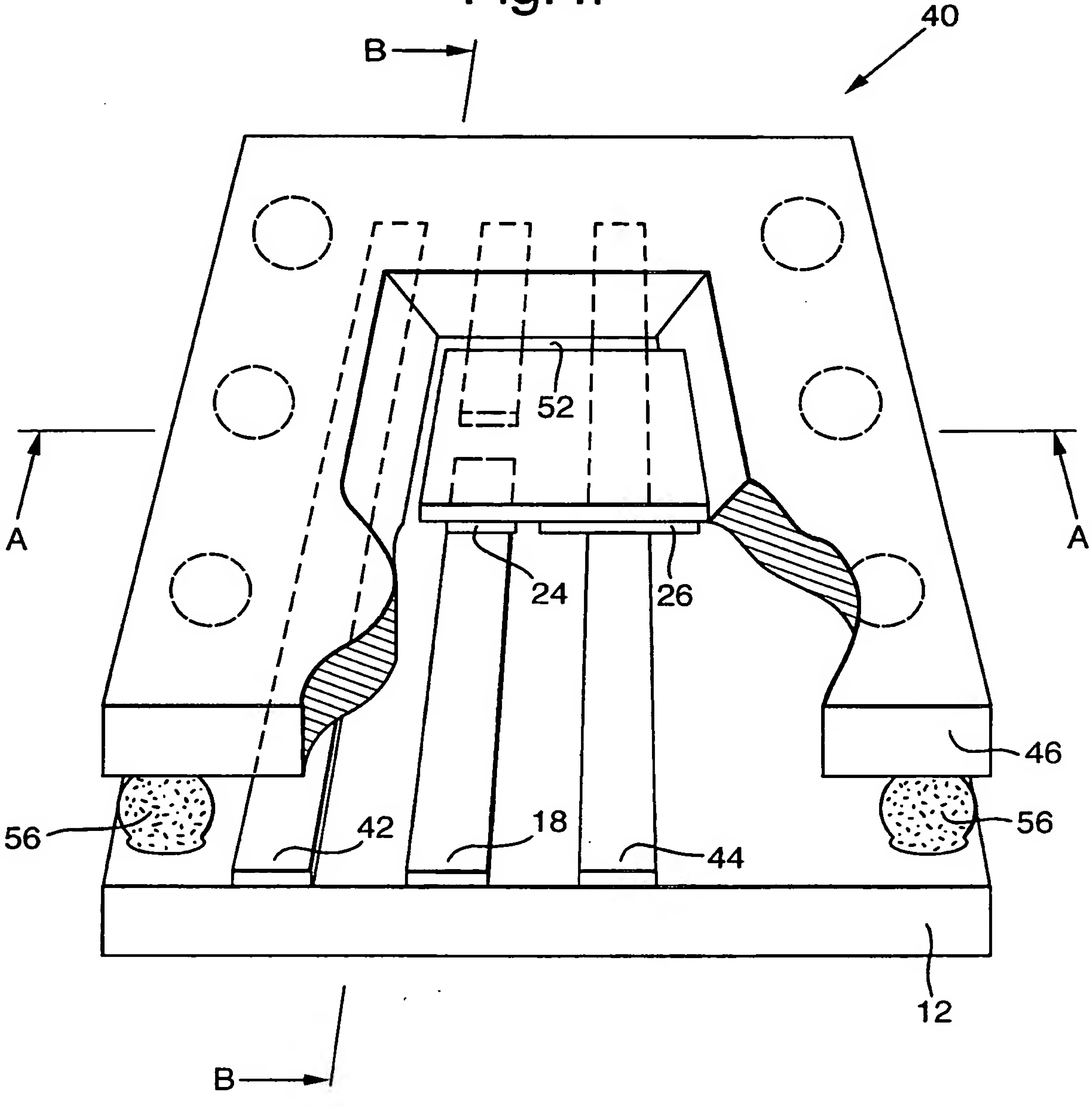

Fig.5.

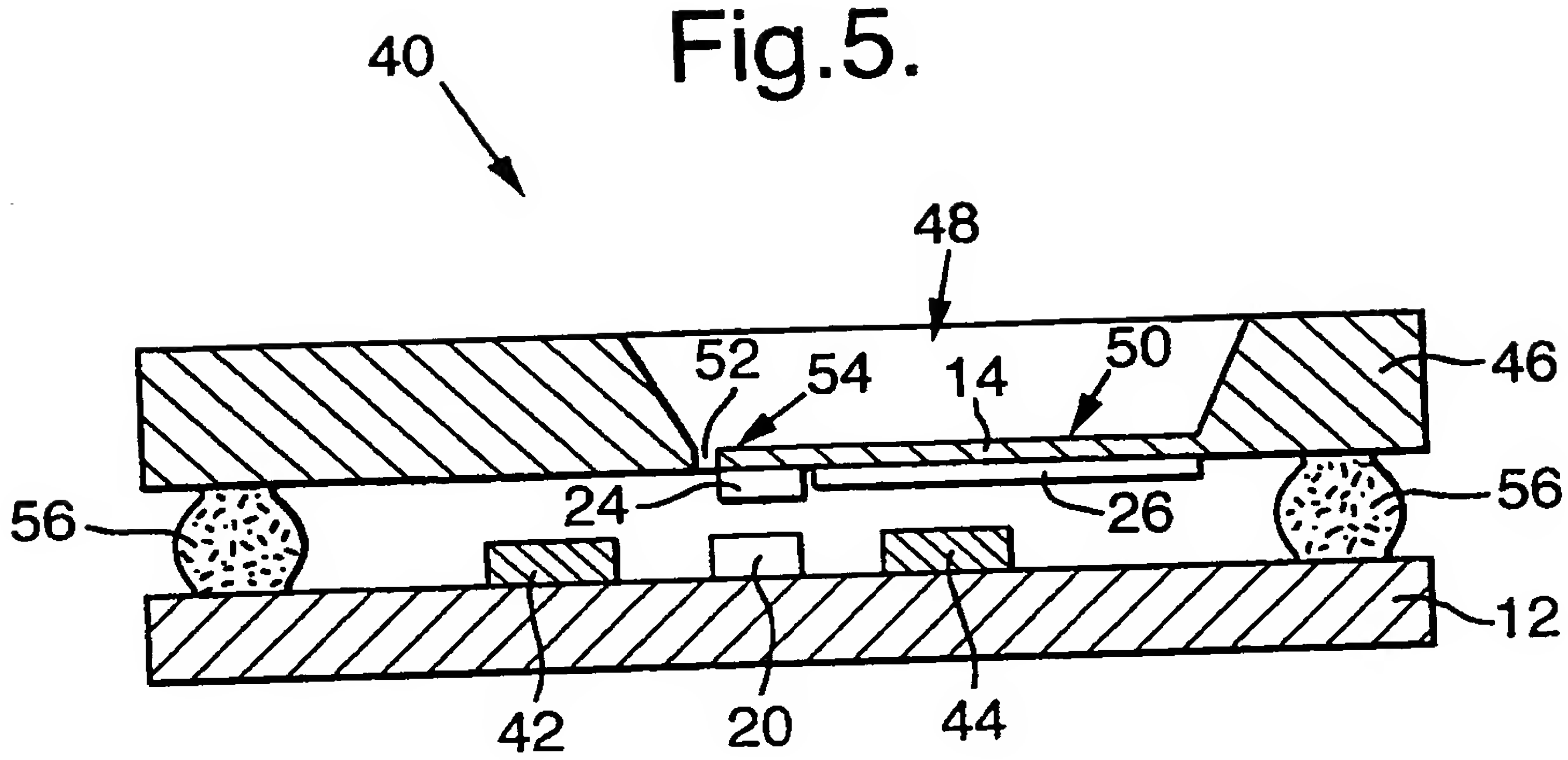
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Fig.6.

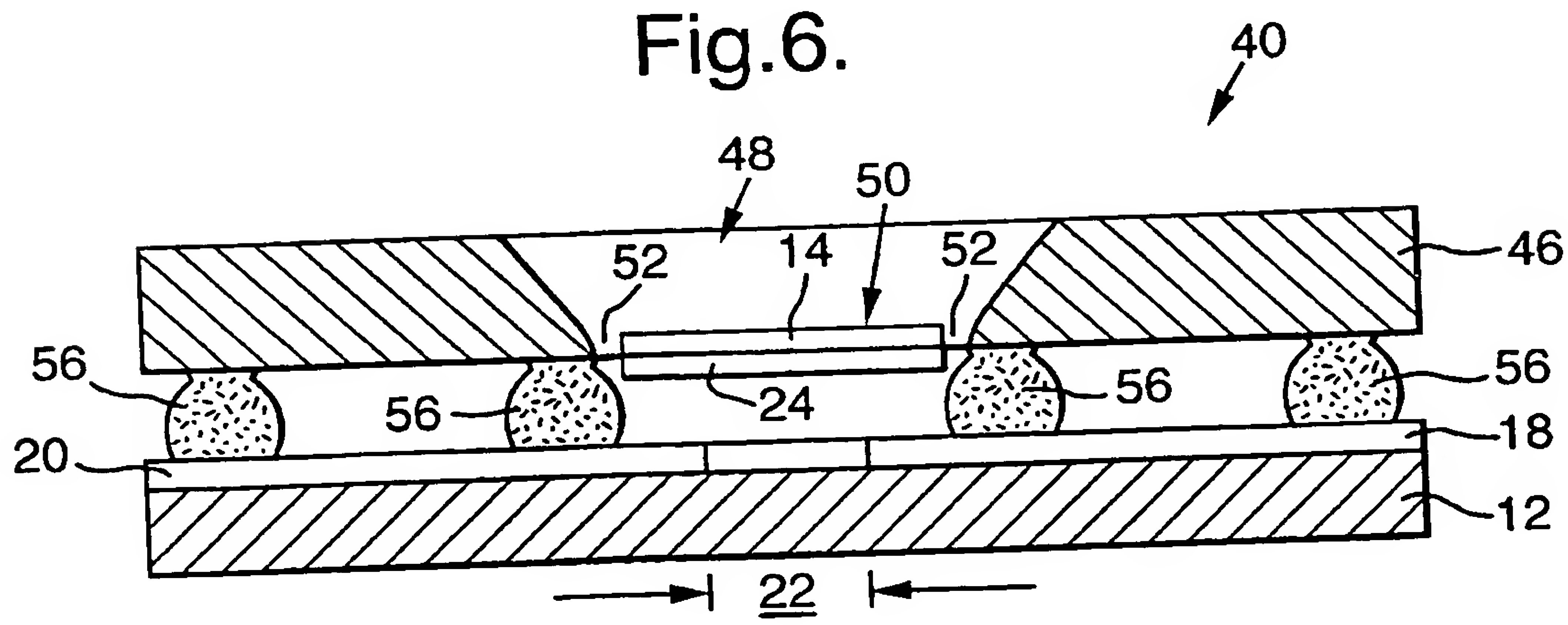
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Fig.7.

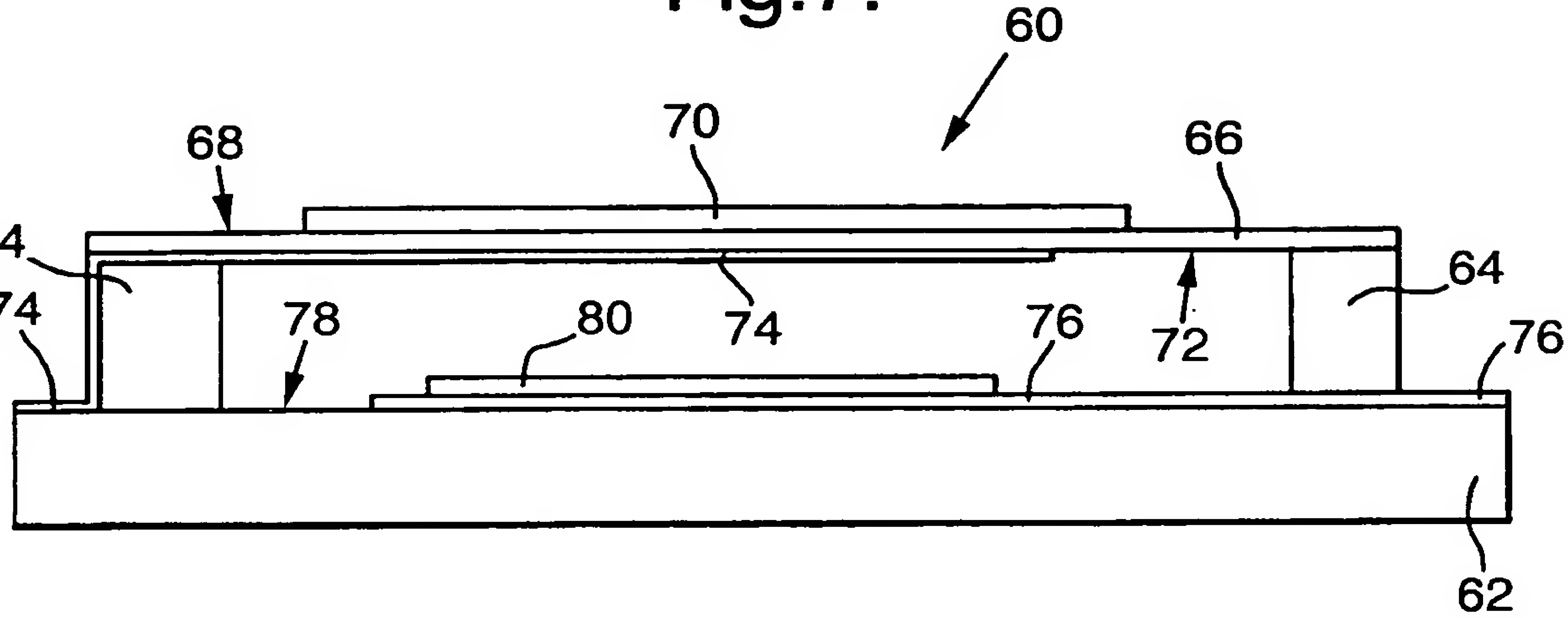
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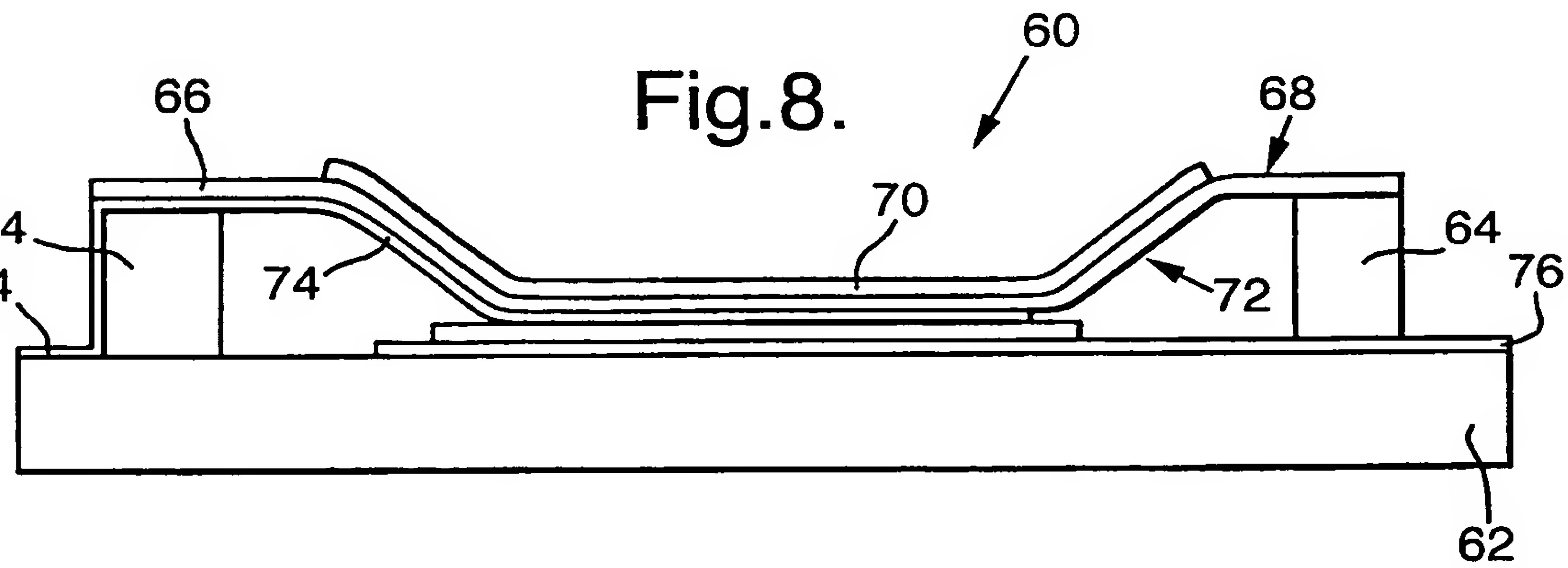
Fig.8.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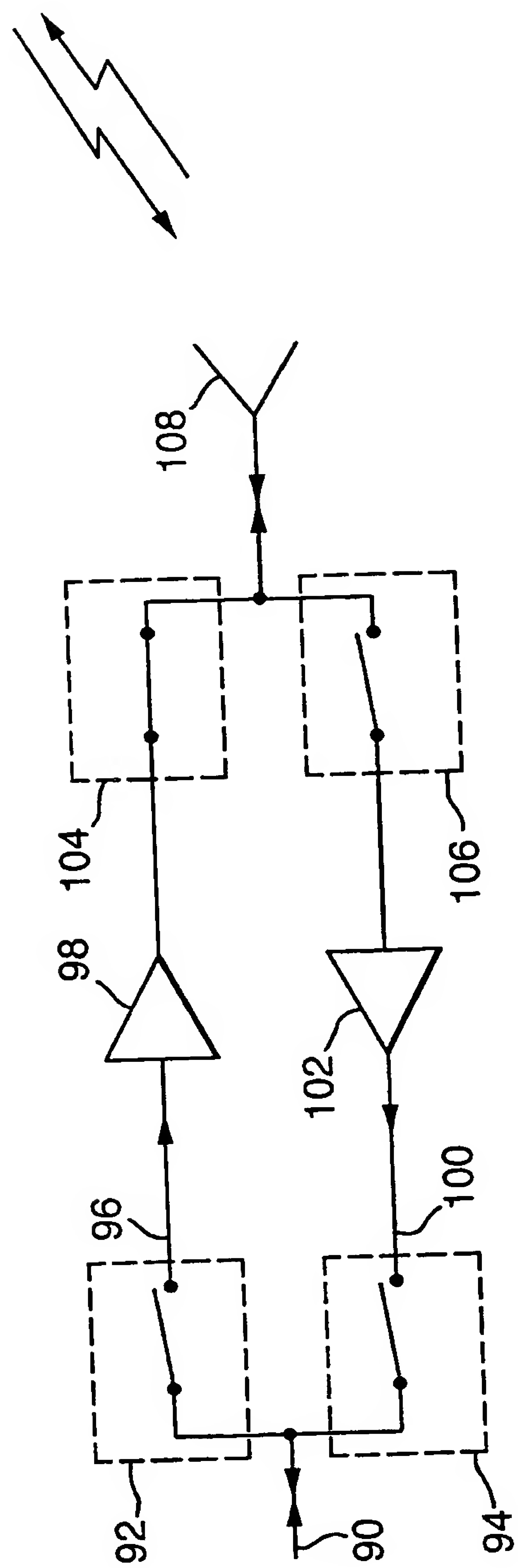

Fig.9.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/03186

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01P1/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01P H01H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 38 15 419 A (PHILIPS PATENTVERWALTUNG GMBH) 16 November 1989 (1989-11-16) column 2, line 67 -column 3, line 50; figures 3,4	1,5,8,10
Y		2-4,6,7, 9,13
Y	DE 43 05 033 A (SIEMENS AG) 28 October 1993 (1993-10-28) column 5, line 26 - line 33	2,3
Y	US 5 796 152 A (CARR ET AL.) 18 August 1998 (1998-08-18) column 1, line 52 - line 61; figures 2A,B,6	4,6,7

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
11 October 2000	19/10/2000

Name and mailing address of the ISA	Authorized officer
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Intern ıal Application No
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